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Relative importance of apoptosis and cell cycle blockage in the synergistic effect of combined R115777 and imatinib treatment in BCR/ABL-positive cell lines

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Abstract

The combination of imatinib and a farnesyltransferase inhibitor might be effective for reducing the number of BCR/ABL-positive leukemia cells. In this study, we examined the differences in the mechanisms of the growth inhibitory effect of the combination of imatinib and R115777 (Zarnestra^{TM}) among BCR/ABL-positive cell lines. Steel and Peckham isobologram analysis indicated that this combination had a strong synergistic inhibitory effect on growth in all imatinib-resistant cell lines and their parental cell lines. Levels of cleaved caspase 3 were increased by the combination treatment in all cell lines. However, both the level of cleaved PARP and the number of annexin-V-positive cells were much less increased in KCL22 and KCL22/SR cells than in K562, KU812, K562/SR and KU812/SR cells. The combination treatment promoted $p27^{KIP1}$ accumulation and induced a significant increase in the percentage of G0/G1 KCL22 and KCL22/SR cells. In other cell lines, the percentage of G0/G1 cells was not increased but rather decreased. The results indicate that induction of apoptosis and blockage of the cell cycle were major mechanisms of the synergistic inhibitory effect of the combination treatment, but the relative importance of these mechanisms differed among cell types. Additional treatment for overriding the G1 checkpoint may be required to eradicate leukemia cells, in which the combination induces cell cycle arrest.

Keywords: R115777; Farnesyltransferase inhibitor; Imatinib; BCR/ABL; Chronic myeloid leukemia; Drug resistance

1. Introduction

The ABL tyrosine kinase inhibitor imatinib mesylate (imatinib, Novartis) has shown a substantial clinical effect in BCR/ABL-positive leukemia patients [1–4]. It has been reported that about 50% of patients with aggressive BCR/ABL-positive leukemia, such as chronic myeloid leukemia in blast crisis (CML-BC) and acute lymphoblastic leukemia (ALL), exhibit a hematological response to treatment with imatinib alone [3,4]. However, most patients with such leukemia relapse soon after showing a response to imatinib; thus, long-term remission is not obtained with imatinib treatment alone. Furthermore, it is possible that many patients with CML-BC will have primary resistance to imatinib because imatinib may already have been administered in the chronic phase in many cases. Previous studies have demonstrated that BCR/ABL gene amplification, point mutations in the ATP-binding pocket of the BCR/ABL gene, increased expression of BCR/ABL protein, up-regulation of P-glycoprotein (P-gp) belonging to the ABC transporter family, increased concentration of serum α1 acid glycoprotein and up-regulation of Nrf2-mediated gene expressions may be involved in the acquisition of resistance to imatinib [5–14]. Several recent studies have indicated that imatinib-resistant cells with a point mutation in the BCR/ABL gene may be present prior to treatment with imatinib in BCR/ABL-positive leukemia patients [5,15–17]. Therefore, to obtain a sufficient clinical effect, it is important to reduce the number of imatinib-resistant leukemia cells by initial treatment targeting aggressive BCR/ABL-positive leukemia. Recently, a new generation of BCR/ABL kinase inhibitors has been developed [18–21] and has been shown to be effective

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against imatinib-resistant cells with point mutations in vitro [18]. However, none of these inhibitors are currently available for clinical use. At present, one attractive therapeutic strategy is combination therapy with imatinib and other anti-leukemia reagents. Cytotoxic effects of various combinations on leukemia cells have been investigated [22,23].

Some cellular proteins, including Ras family proteins, require posttranslational modifications to become active. Prenylation, which is involved in these modifications, can be performed by adding a 15-carbon farnesyl isoprenoid group mediated by farnesyltransferase. An alternative prenylation reaction, geranylgeranylation, can be performed by transferring a 20-carbon geranylgeranyl isoprenoid to proteins by geranylgeranyl transferases. Because prenylation is required to transfer Ras proteins to the cellular membrane, farnesyltransferase inhibitors (FTIs) were initially expected to suppress Ras function, leading to tumor growth inhibition [24,25]. An FTI showed significant anti-tumor activity via inhibition of H-Ras function in an activated H-Ras-induced breast cancer model [26]. However, N-Ras and K-Ras can be transferred to the cellular membrane by geranylgeranylation, even if farnesylation is inhibited, suggesting that inhibition of the processing of other target proteins is involved in the anti-tumor effects of FTIs. Such target proteins may include the small GTP-binding protein RhoB and the centromere-associated proteins CENP-E and CENP-F [27,28].

FTIs have been shown to have anti-leukemia effects on BCR/ABL-positive cultured cells and in BCR/ABL-positive murine models [29,30]. Moreover, Hoover et al. reported that an FTI, SCH66336, inhibited proliferation of imatinib-resistant cell lines and colony formation by hematopoietic progenitors from imatinib-resistant CML patients [31]. These findings suggest that FTIs have potential as agents for treatment of imatinib-resistant BCR/ABL-positive leukemia. The results of clinical studies on an FTI, R115777 (Zarnestra^{TM}, Titusville, NJ), indicate that it is moderately effective against CML [32,33]. However, R115777 alone does not seem to be sufficiently effective against aggressive CML [33]. Phase I studies using combination therapy with R115777 and imatinib for treatment of refractory or resistant BCR/ABL-positive leukemia have been conducted [34,35].

In this study, we investigated the mechanisms underlying the inhibitory effect of the combination of R115777 and imatinib on growth of BCR/ABL-positive cells. Our isobologram analysis revealed that this combination has a significant synergistic inhibitory effect on growth of imatinib-resistant cell lines and imatinib-sensitive cell lines. We also found that this effect was due to both induction of apoptosis and blockage of the cell cycle, but the relative importance of these two mechanisms differed among cell lines.

2. Materials and methods

2.1. Cell lines

We previously established an imatinib-resistant clone, KCL22/SR, from the KCL22 human BCR/ABL-positive cell line [36]. To obtain other imatinib-resistant clones, we treated K562 and KU812 cells (BCR/ABL-positive cell lines established from peripheral blood of CML patients in blast crisis) with step-wise increasing concentrations of imatinib (0.1–1.0 μM) and cultured them on a medium containing methylcellulose, followed by selection and cloning of individual colonies. These newly cloned imatinib-resistant cell lines were designated K562/SR and KU812/SR, respectively. All imatinib-sensitive parental cells and imatinib-resistant cells were grown in RPMI1640 medium supplemented with 10% fetal bovine serum and split every 4 days.

2.2. Cytotoxic effects of a combination of R115777 and imatinib

The farnesyltransferase inhibitor R115777 was kindly provided by Johnson & Johnson Pharmaceutical and Development (Philadelphia, PA). Imatinib was purchased from Novartis Pharma (Basel, Switzerland). Cells were incubated with various concentrations of each reagent for 4 days and then cell numbers were counted using a Cell Counting Kit-8 (Wako Pure Chemical Industries Ltd. Osaka, Japan) in accordance with the manufacturer's instructions. The cytotoxic effect of the combination of R115777 and imatinib was evaluated by a Steel and Peckham isobologram as described previously [37,38]. When the points were outside the left margin of the envelope formed by two broken lines, the combination treatment was considered to have a synergistic effect on cell growth inhibition. If the points were plotted within the envelope, the combination treatment was considered to have an additive effect.

2.3. Western blot analysis

Whole cell lysates were prepared from 1×10^7 cells according to a method described previously [39]. Then 10 μg of whole cell lysate was separated electrophoretically using 10% polyacrylamide gel. Immunoblotting and detection by enhanced chemiluminescence were performed as described previously [40]. Mouse anti-glyceraldehyde-3-phosphate dehydrogenase monoclonal antibody and anti-phospho-tyrosine antibody were purchased from Chemicon International (Temecula, CA) and Santa Cruz Biotechnology (Santa Cruz, CA), respectively. Anti-cleaved caspase 3, anti-PARP, anti-p44/42 (ERK1/2) MAP kinase and anti-phospho p44/42 (ERK1/2) MAP kinase rabbit polyclonal antibodies were purchased from Cell Signaling Technology (Beverly, MA). Mouse anti-

$p27^{KIP1}$ and anti-HDJ-2 monoclonal antibodies were purchased from BD Biosciences (San Jose, CA) and Neomarkers (Fremont, CA), respectively.

2.4. Flow cytometry

Apoptotic cells were evaluated by counting annexin-V-positive cells using a MEBCYTO-Apoptosis Kit (MBL, Nagoya, Japan) in accordance with the manufacturer's instructions. Briefly, the cells were collected and rinsed once with phosphate-buffered saline (PBS). The cells were then incubated with annexin-V-FITC and propidium iodide for 15 min and analyzed by flow cytometry using a FACScan Analyzer (Becton Dickinson, San Jose, CA). For cell cycle analysis, the cells were incubated with propidium iodide for 30 min and analyzed by flow cytometry using a FACScan/CellFIT system (Becton Dickinson, San Jose, CA).

3. Results

3.1. Development of imatinib-resistant BCR/ABL-positive cell lines

We used an imatinib-resistant clone, KCL22/SR, and its parental BCR/ABL-positive cell line, KCL22 [36]. In addition, we cloned two other imatinib-resistant clones, K562/SR and KU812/SR, from the BCR/ABL-positive cell lines K562 and KU812, respectively. As shown in Table 1, IC_{50} values of imatinib against the three imatinib-resistant clones were 5–9-fold higher than that against each corresponding parental cell line. No amplification of or point mutation in the BCR/ABL gene was found in these imatinib-resistant clones. Consistent with our previous findings [36], imatinib treatment resulted in a significant decrease in the level of phosphorylation of BCR/ABL protein in all imatinib-resistant clones as well as parental cell lines (data not shown). These results suggest that deregulation of processes downstream of BCR/ABL kinase is involved in the acquisition of resistance to imatinib in these imatinib-resistant clones.

3.2. Combined treatment of BCR/ABL-positive cells with R115777 and imatinib resulted in synergistic inhibition of cell growth

To confirm that the farnesyltransferase inhibitor R115777 inhibits farnesylation in BCR/ABL-positive cells, we examined the level of the chaperone protein HDJ-2, which is a substrate of farnesyltransferase, by Western blot analysis using an anti-HDJ-2 antibody [41]. Treatment of cells with R115777 resulted in significant accumulation of unprocessed HDJ-2 in all cell lines (data not shown), suggesting that farnesylation is effectively inhibited by R115777 in both imatinib-sensitive and imatinib-resistant BCR/ABL-positive cells. To determine whether a combination of R115777 and imatinib effectively inhibits growth of BCR/ABL-positive cells, we examined the time courses of changes in cell count after treatment with IC_{50} concentrations of imatinib, R115777 and a combination of these two reagents. The combined treatment resulted in greater suppression of cell growth than did treatment with either of the reagents alone in all parental and imatinib-resistant cells (data not shown). To determine whether the growth inhibitory effect was synergistic or additive, we next performed Steel and Peckham isobologram analysis, which provides very strict and reliable results [38]. Combined treatment of parental cells (KCL22, K562 and KU812) with R115777 and imatinib resulted in clear synergistic inhibition of cell growth (Fig. 1A). This combination also synergistically inhibited the growth of imatinib-resistant cells, KCL22/SR, K562/SR and KU812/SR (Fig. 1A). These results indicate that the combination of R115777 and imatinib has a synergistic inhibitory effect on growth of BCR/ABL-positive cells, regardless of sensitivity to imatinib.

R115777 was initially expected to be an inhibitor of Ras function. We investigated the levels of phosphorylation of ERK1/2, a Ras-mitogen-activated protein kinase (MAPK), to determine whether the synergistic inhibitory effect was mediated by alteration of Ras signaling. However, the levels of phopho-ERK1/2 were not decreased by R115777 treatment in any of the cell lines (data not shown). These results suggest that inhibition of Ras-MAPK signaling is not involved in the inhibitory effect of R115777 on BCR/ABL-positive cells.

Table 1
IC_{50} values of imatinib against the imatinib-sensitive and the imatinib-resistant cell lines

IC_{50} values(μM)		
KCL22 0.199 ± 0.037	KCL22/SR 1.779 ± 0.934	Ratio ×8.940
K562 0.218 ± 0.091	K562/SR 1.245 ± 0.419	Ratio ×5.711
KU812 0.216 ± 0.076	KU812/SR 1.526 ± 0.308	Ratio ×7.065

3.3. R115777 and imatinib synergistically inhibited the growth of leukemia cells from a patient in blast crisis

We next examined the effect of combined treatment on the growth of primary leukemia cells from a 53-year-old male patient in imatinib-resistant blast crisis. Written informed consent for the examination was obtained from the patient. Leukemia cells from peripheral blood of the patient, with no mutation in the BCR/ABL gene, were used for Steel and Peckham isobologram analysis. The patient showed no response to imatinib after conversion to blast crisis. The IC_{50} of imatinib to these cells was 0.71 μM, which is high compared with those of imatinib-sensitive CML cell lines. Combined treatment of these cells with R115777 and imatinib resulted in a synergistic inhibitory effect on growth (Fig. 1B). These results suggest that this combination treatment is effective against primary imati-

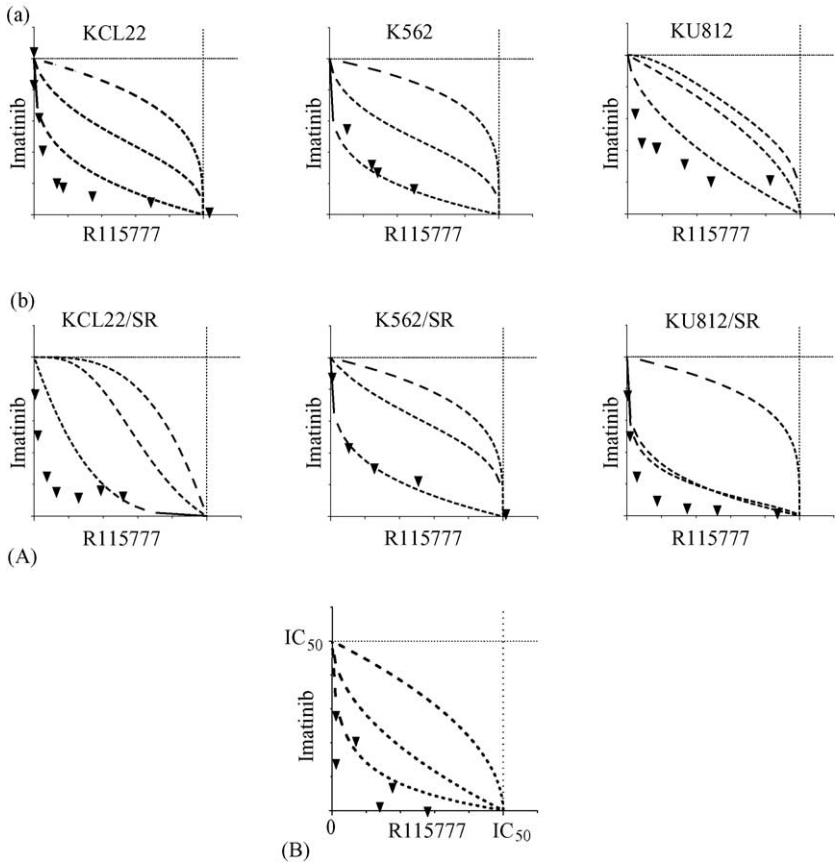

Fig. 1. Effect of combination of R115777 and imatinib on growth inhibition. (A) Steel and Peckham isobologram analyses of the combination of R115777 and imatinib in BCR/ABL-positive cell lines were performed as described in Section 2. Most points are plotted in the area representing synergistic effects in all BCR/ABL-positive parental cell lines (a) and imatinib-resistant cell lines (b). (B) Mononuclear cells from peripheral blood of a patient with imatinib-refractory blast crisis were first seeded at a density of 1×10^5 cells/ml and cultured in RPMI1640 media for 72 h. Steel and Peckham isobologram analysis of the combination of R115777 and imatinib was performed as described in Section 2. Most points are plotted in the area of synergistic effects.

nib-resistant BCR/ABL-positive cells in patients in blast crisis.

3.4. Induction of apoptosis by combination of R115777 and imatinib

To clarify whether the combination of R115777 and imatinib inhibits cell growth due to induction of apoptosis, we examined the levels of cleaved caspase 3, cleaved PARP and the number of annexin-V-positive cells with or without the combination treatment. The combination treatment increased the level of cleaved caspase 3 in all parental and imatinib-resistant cell lines (Fig. 2A). In K562, K562/SR, KU812 and KU812/SR cells, the level of cleaved PARP, which is one of the downstream molecules of caspase 3, was also significantly increased. Consistent with these results, the combination treatment markedly increased the number of annexin-V-positive K562, K562/SR, KU812 and KU812/SR cells, whereas addition of IC_{50} concentrations of imatinib or R115777 alone only slightly increased the number of annexin-V-positive cells (Fig. 2B). In contrast, the level of cleaved PARP was much less increased by the combination treatment in KCL22 and KCL22/SR cells (Fig. 2A). Furthermore, induction of annexin-V-positive cells was much less pronounced in KCL22 and KCL22/SR cells at 72 h (Fig. 2B), 48 h and 96 h (data not shown) after addition of R11577 with imatinib. These results indicate that the combination of R11577 and imatinib induces apoptosis in both imatinib-sensitive and imatinib-resistant cells, but the contribution of apoptosis to the synergistic inhibitory effect on cell growth is relatively low in KCL22 and KCL22/SR cells because of insufficient activation of PARP.

3.5. Effect of the combination of R115777 and imatinib on the cell cycle

Since the combination treatment only slightly increased the number of annexin-V-positive cells in KCL22 and KCL22/SR cells, we hypothesized that the synergistic growth inhibition was mainly caused by induction of cell cycle blockage in these cells. To investigate the function of the G1 checkpoint, we first examined the level of $p27^{KIP1}$. Consistent with our previous findings, $p27^{KIP1}$ expression was up-regulated by treatment with imatinib alone in

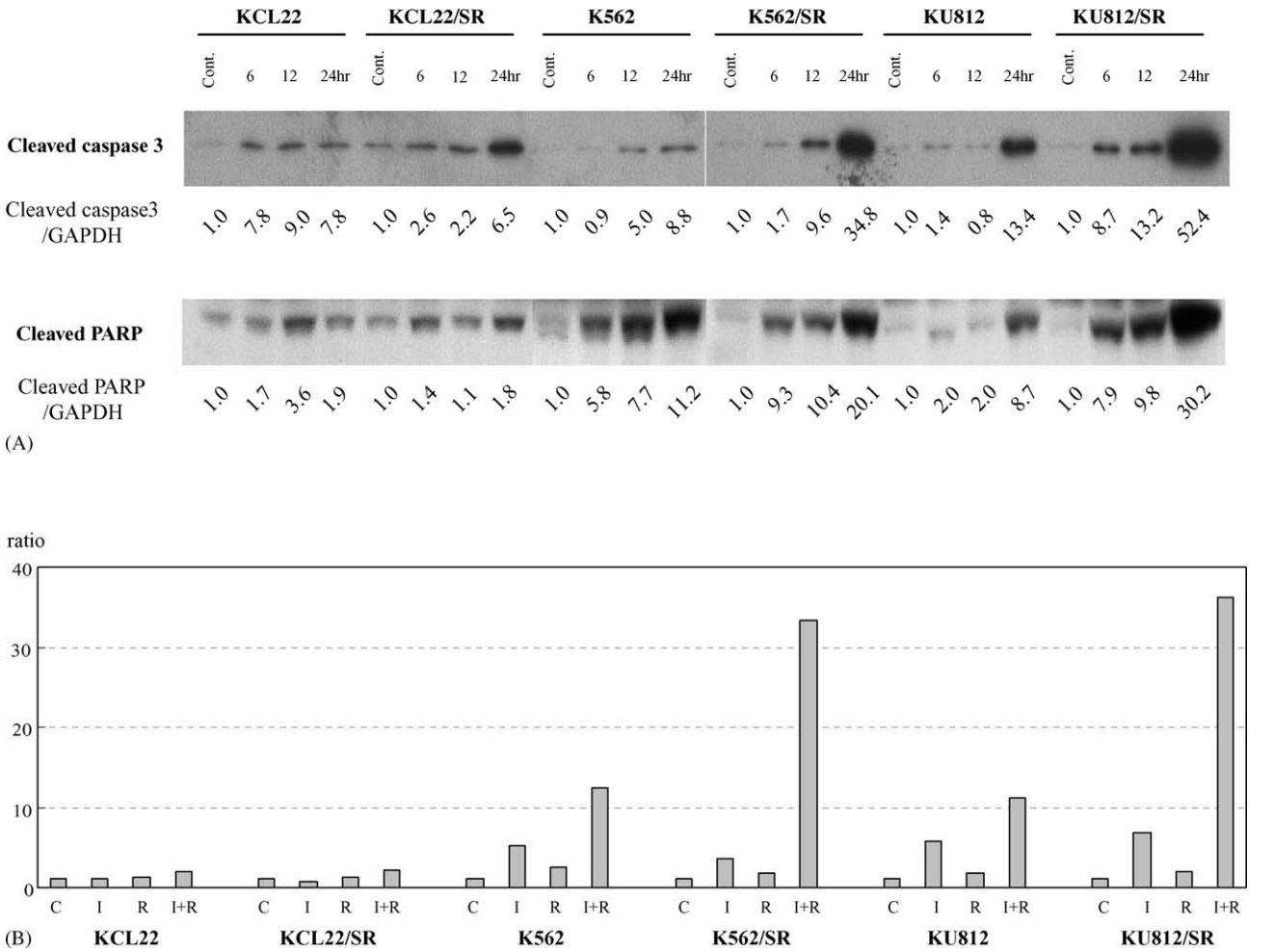

Fig. 2. Induction of apoptosis by a combination of R115777 and imatinib. (A) Cells were cultured in the absence of any reagent for 3 days prior to the treatment and then treated with a combination of IC_{50} concentrations of imatinib and R115777 for 6, 12 and 24 h. Total cell lysates were prepared and subjected to Western blot analysis using anti-cleaved casepase-3 and anti-PARP antibodies. The expression of glyceraldehyde-3-phosphate dehydrogenase (GAPDH) was examined as an internal control. The levels of cleaved caspase 3 and cleaved PARP normalized on the basis of GAPDH levels are shown. (B) Cells were cultured in the absence of any reagent for 3 days prior to treatment and then treated with IC_{50} concentrations of imatinib, R115777 or a combination of imatinib and R115777 for 72 h. The number of annexin-V-positive cells was counted by flow cytometry as described in Section 2.

KCL22 and KCL22/SR cells (Fig. 3A). In these cells, the combination treatment with IC_{50} concentrations of R115777 and imatinib also promoted $p27^{KIP1}$ accumulation and significantly increased the percentage of G0/G1 cells (Fig. 3A and B). To determine whether a higher concentration of imatinib could induce cell cycle progression and thus lead cells to apoptosis, we next examined the effect of combined treatment with 5 μM imatinib and IC_{50} concentration of R115777 on $p27^{KIP1}$ expression and G0/G1 accumulation. The results showed that the combination of the reagents at these concentrations increased $p27^{KIP1}$ level and the percentage of G0/G1 cells to the same level and percentage as those in the case of IC_{50} concentrations of R115777 and imatinib (data not shown). These findings suggest that the combination could not abrogate the imatinib-induced activation of G1 checkpoint and that induction of cell cycle arrest rather than induction of apoptosis was thus the main cause of synergistic growth inhibition in KCL22 and KCL22/SR cells. In contrast, the percentage of G0/G1 cells among K562, KU812, K562/SR or KU812/SR cells was not increased but rather decreased by combination treatment (Fig. 3B). Consistent with these results, the levels of cycline D1 were decreased after combination treatment in K562, KU812, K562/SR and KU812/SR cells (data not shown). The $p27^{KIP1}$ level in KU812/SR cells was slightly increased and maintained for 24 h by treatment with imatinib alone, whereas the level was increased at 6 h but declined afterward in K562, K562/SR and KU812 cells (Fig. 3A). Interestingly, combination treatment with R115777 and imatinib had no inhibitory effect on the imatinib-mediated induction of $p27^{KIP1}$ expression in these cells (Fig. 3A). These results suggest that G0/G1 accumulation was not induced in these cells, unlike in KCL22 and KCL22/SR cells, despite G1 checkpoint activation, probably due to the significant induction of apoptosis after combination treatment.

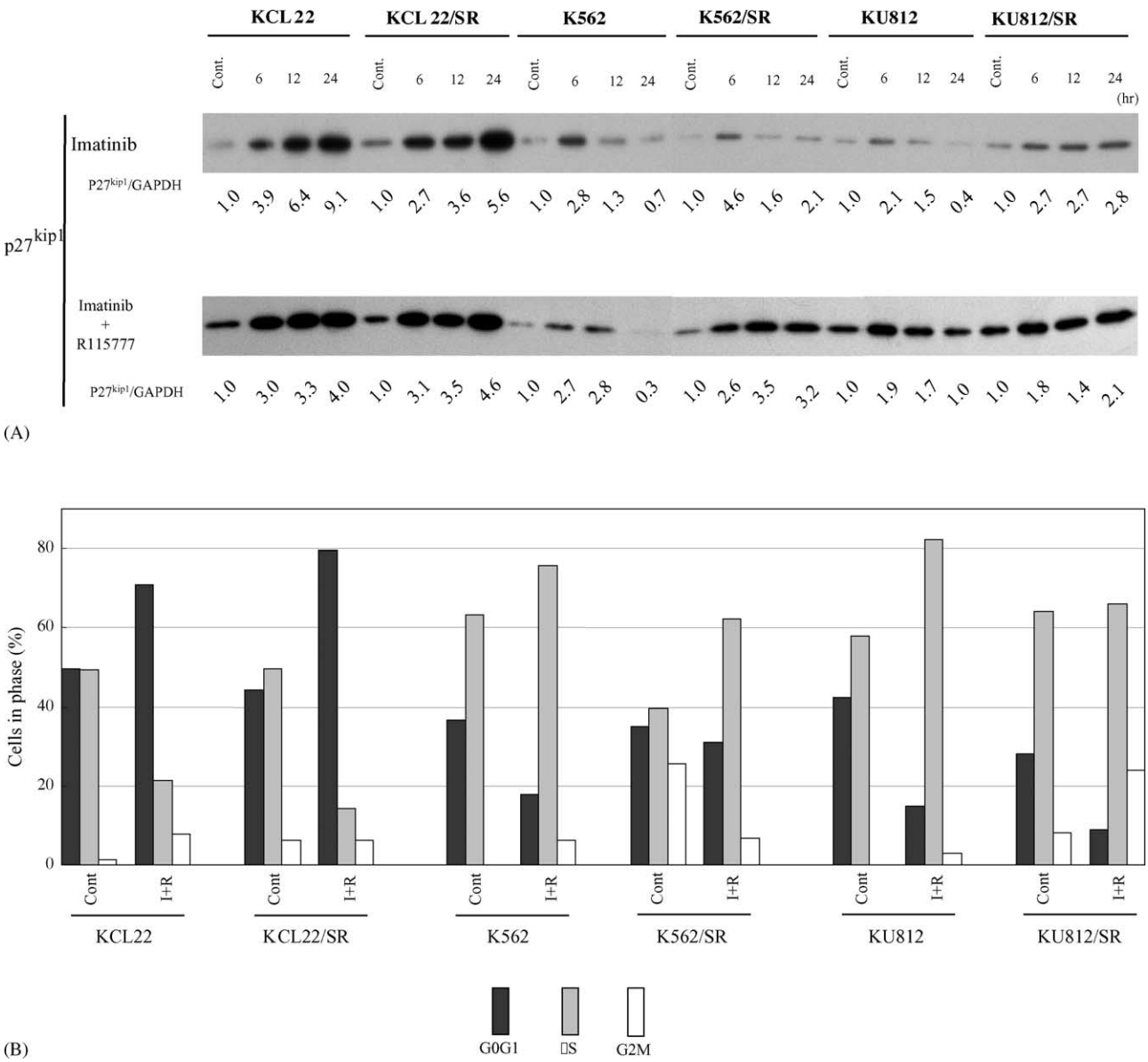

Fig. 3. Effect of combination treatment with R115777 and imatinib on the cell cycle. (A) Changes in $p27^{KIP1}$ protein levels in cells treated with imatinib alone or with a combination of R115777 and imatinib. Cells were cultured in the absence of any reagent for 3 days prior to the treatment and then treated with IC_{50} concentrations of imatinib alone or a combination of IC_{50} concentrations of imatinib and R115777 for 6, 12 and 24 h. Total cell lysates were prepared and subjected to Western blot analysis using anti-$p27^{KIP1}$ antibody. Anti-glyceraldehyde-3-phosphate dehydrogenase (GAPDH) antibody was used as a control for loading (lower panel). (B) Combination treatment of R115777 and imatinib changed the ratios of cell cycle stages. After 24 h of incubation of cells with IC_{50} concentrations of imatinib and R115777, the cells were harvested and incubated with propidium iodide for 30 min and analyzed by flow cytometry with a FACScan/CellFIT system (Becton Dickinson, San Jose, CA).

4. Discussion

Previous studies showed that sustenance of BCR/ABL kinase activity mediated by mechanisms including increased expression of and point mutations in the BCR/ABL gene is a major cause of acquisition of resistance to imatinib [5–14]. In fact, BCR/ABL gene mutations have been found in many clinical imatinib-resistant cases [5–9]. However, there are some cases in which no mutation is found. In the latter cases, deregulation of processes downstream of BCR/ABL kinase may be involved in the resistance to imatinib. Thus, resistance to imatinib can apparently be obtained in both BCR/ABL kinase activity-related and activity-unrelated manners. Imatinib-resistant cell lines examined in the present study exhibited no upregulation of BCR/ABL protein or point mutations in the BCR/ABL gene (data not shown). Moreover, phosphorylation of BCR/ABL was significantly suppressed by imatinib treatment, suggesting that these cells provide a good model of imatinib resistance via a BCR/ABL kinase activity-unrelated mechanism.

FTIs are reagents that may target abnormally activated cellular signaling downstream of BCR/ABL kinase. Previous in vitro studies showed that combinations of FTIs and

imatinib are effective against BCR/ABL-positive cells, but it is unclear whether this effect is additive or synergistic. The present results indicate that combination of R115777 and imatinib synergistically inhibits growth of BCR/ABL-positive cell lines, as indicated by a Steel and Peckham isobologram, which is one of the most reliable methods of analysis for evaluating cell growth inhibition (Fig. 1A). Notably, this synergistic inhibitory effect was also observed in both imatinib-resistant cell lines and leukemia cells from an imatinib-refractory patient (Fig. 1A and B). These results strongly suggest that this combination would have therapeutic value for patients with aggressive BCR/ABL-positive leukemia. It is important to clarify whether the combination treatment is also effective against cells that have resistance-associated mutated BCR/ABL protein, whose kinase activity is not effectively inhibited by imatinib [42]. On the other hand, the contribution of upregulation of P-gp to acquisition of resistance to imatinib is still controversial [43,44]. Fortunately, the effect of the combination treatment may not be influenced by overexpression of P-gp, because the growth of KU812/SR cells (which express P-gp at a level 12.7-fold higher than that in parental KU812 cells) was effectively inhibited by the combination treatment, as was the case with other cell lines.

FTIs were initially developed as inhibitors of posttranslational processing of Ras proteins. However, numerous previous studies suggest that inhibition of the processing of other target proteins such as RhoB, CENP-E and CENP-F is involved in FTI-mediated inhibition of tumor cell proliferation [27,28]. In the present study, R115777 alone had no effect on the levels of phopho-ERK1/2 in any of the BCR/ABL-positive cell lines examined. Taken together with the finding that overexpression of MEK1 (a downstream kinase in the Ras pathway) in KCL22 cells did not restore the cytotoxic effect of the combination treatment (data not shown), this suggests that inhibition of abnormally activated signaling other than Ras-MAPK signaling is involved in synergistic growth inhibition by the combination treatment. We previously found by DNA microarray analyses that RASAP1 and RhoA, which affect or engage in cross talk with cellular signaling, are expressed at higher levels in KCL22/SR cells than in KCL22 cells [36]. It is of interest to clarify whether the effect of the combination treatment is mediated by expression of such molecules.

It has been shown that imatinib induces apoptosis in CML cells [45]. In K562, KU812, K562/SR and KU812/SR cells, R115777 significantly augmented the imatinib-induced increase in the number of annexin-V-positive cells (Fig. 2B). Consistent with these results, the levels of both cleaved caspase 3 and cleaved PARP were increased by the combination treatment. These results suggest that the combination effectively induces apoptosis in these cells. In contrast, the induction of annexin-V-positive cells was extremely low in KCL22 and KCL22/SR cells despite the increase in the level of cleaved caspase 3 by the combination treatment (Fig. 2A and B). One possible explanation for these results is that apoptosis signaling was blocked downstream of caspase 3 in KCL22 and KCL22/SR cells. In fact, the level of cleaved PARP, which is one of the downstream molecules of caspase 3, was much less increased in KCL22 and KCL22/SR cells than in other cell lines (Fig. 2A). Although it is also possible that other unknown mechanisms critically contribute to the blockage of apoptosis, these results suggest that the apoptosis-induction system may break down and that even the combination could not overcome the resistance for the induction of apoptosis in these cells. It is of importance to elucidate the possible unknown mechanisms of apoptosis signaling blockage, and such efforts are now being made in our laboratory.

$p27^{KIP1}$ expression was up-regulated by imatinib alone in all cell lines examined in this study. These results are consistent with our previous findings that imatinib induced cell cycle arrest at the G0/G1 phase, accompanied by up-regulation of $p27^{KIP1}$, in KCL22 cells [46]. Addition of R115777 resulted in no suppression of imatinib-induced up-regulation of $p27^{KIP1}$ expression in all cell lines, suggesting that the combination could not inhibit imatinib-dependent activation of the G1 checkpoint. It is noteworthy that R115777 alone increased the $p27^{KIP1}$ level (in K562, KU812, KCL22 and KCL22/SR cells) or had no effect on the $p27^{KIP1}$ level (in K562/SR and KU812/SR cells) (data not shown). Since FTIs have been shown to induce cell cycle arrest via inhibition of farnesylation of CENP-E protein [47,48], it is possible that CENP-E was a target molecule of R115777 in these cells. Since the apoptosis signal was blocked downstream of caspase 3, the percentage of G0/G1 cells was significantly increased with G1 checkpoint activation after the combination treatment in KCL22 and KCL22/SR cells (Fig. 3A and B). Therefore, it is concluded that cell cycle blockage was mainly involved in the synergistic cell growth inhibition by the combination treatment in KCL22 and KCL22/SR cells. We previously showed that treatment of KCL22 cells with 20 μM imatinib also resulted in G0/G1 accumulation but not in induction of apoptosis [46]. In this study, combined treatment of KCL22 and KCL22/SR cells with R115777 and a higher concentration (5 μM) of imatinib also resulted in G0/G1 accumulation (data not shown). These results suggest that a high concentration of imatinib could not overcome G1 checkpoint activation in these cells.

The other cell lines, K562, KU812, K562/SR and KU812/SR, exhibited different responses. Although the level of $p27^{KIP1}$ was increased by the combined treatment, the percentage of G0/G1 cells was not increased but was rather decreased. The reason for these discrepant phenomena may be the significant induction of apoptosis in these cells. It is likely that apoptosis is induced in the cells before they are led to a G0/G1 state. These results suggest that the induction of apoptosis but not cell cycle blockage plays an important role in the synergistic growth inhibition of K562,

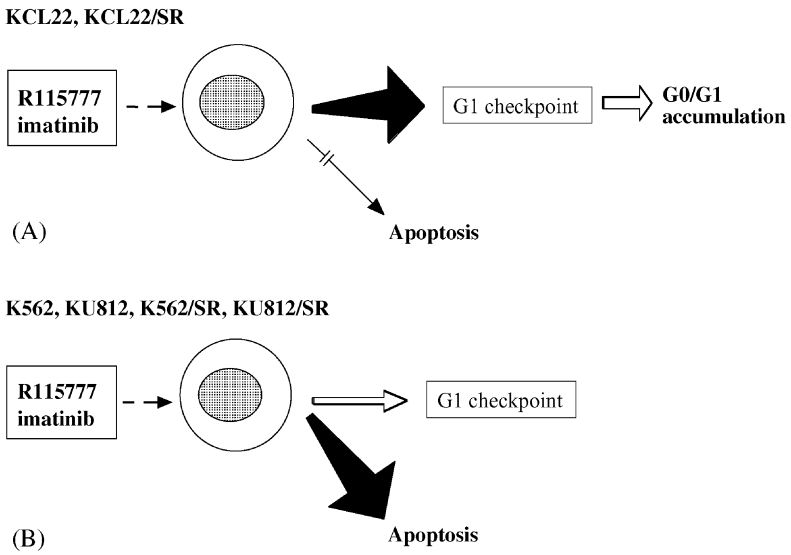

Fig. 4. Hypothetical scheme of the different responses to the combination of R115777 and imatinib in BCR/ABL-positive cells. (A) The combination treatment activates the G1 checkpoint, leading to G0/G1-phase accumulation in KCL22 and KCL22/SR cells, in which apoptosis signaling breaks down. (B) K562, KU812, K562/SR and KU812/SR cells undergo apoptosis with the combination treatment without induction of G0/G1 accumulation.

KU812, K562/SR and KU812/SR cells. A model for the different responses to the combination treatment is presented in Fig. 4. This predicts that the G1 checkpoint remains active but apoptosis signaling breaks down under the condition of combination treatment, leading to G0/G1-phase accumulation in KCL22 and KCL22/SR cells. In contrast, K562, KU812, K562/SR and KU812/SR cells mainly undergo apoptosis by the combination treatment. It is interesting that the imatinib-resistant clone and each corresponding parental cell line showed similar responses to the combination treatment. Therefore, the different pattern of responses might be due to some original cell characteristics, which remain even after acquisition of resistance to imatinib.

The results of this study suggest that the combination treatment of R115777 and imatinib effectively reduce the number of leukemia cells regardless of the sensitivity to imatinib. The finding that the relative importance of the two major mechanisms involved in synergistic inhibition, induction of apoptosis and cell cycle blockage, differed among cell types may have important implications for clinical application of the combination treatment. Since primitive, quiescent BCR/ABL-positive cells may be resistant to imatinib [49], it is likely that KCL22 or KCL22/SR-type leukemia cells, the cell cycles of which are induced to a standstill, may survive after the combination treatment and grow later in the clinical course. Therefore, additional treatment for overriding the G1 checkpoint may be required to eradicate these types of leukemia cells.

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